BBC RD 1993/12

Research Department Report

PREDICTED COVERAGE OF A COFDM SINGLE FREQUENCY NETWORK FOR UHF DIGITAL TERRESTRIAL TV BROADCASTING

M.B.R. Lee, Ph.D., D.I.C., A.M.I.E.E.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

BBC RD 1993/12

PREDICTED COVERAGE OF A COFDM SINGLE FREQUENCY NETWORK FOR UHF DIGITAL TERRESTRIAL TV BROADCASTING

M.B.R. Lee, Ph.D., D.I.C., A.M.I.E.E.

Summary

The Coded Orthogonal Frequency Division Multiplex (COFDM) transmission system provides a very high degree of tolerance towards multipath interference. Three factors contribute towards this tolerance; the inclusion of a guard interval, coding to provide error correction and the division of the digital data amongst a very large number of low bit rate carriers. It follows from this that a national network of co-channel transmitters can be developed such that not only do neighbouring transmitters not cause mutual interference but can combine in a constructive manner. This is the principle of the Single Frequency Network, or SFN.

Experience with Digital Audio Broadcasting (DAB) suggests that an SFN could be utilised for Digital Video Broadcasting (DVB). Such a system would make very efficient use of the available UHF channels. The Report presents the results of coverage predictions performed for a network of 128 transmitters sited at the locations of existing high and medium power UK UHF broadcast transmitters. Predictions were carried out for a range of values of guard interval, and for both directional and omnidirectional receiving antennas.

Use of COFDM and the latest data compression techniques allows a High Definition Television (HDTV) programme to be transmitted in a standard UHF channel. However it will require a higher-order modulation scheme than is used for DAB. This will reduce the tolerance towards noise and interference. The guard interval may therefore have to be lengthened so that signals from more distant transmitters within the network arrive within the guard interval.

The results of the predictions show that the ad hoc transmitter network examined will serve 90% or more of the UK population, using the same guard interval as has been chosen for Mode 1 of the Eureka DAB system, provided that a directional antenna is used. The directional antenna provides most of the extra protection required against interfering signals. The same coverage can be obtained using an omnidirectional antenna if the guard interval is doubled. Alternatively the data could be coded in such a way that a standard definition picture is produced if the level of interference is too high for HDTV.

Issued under the Authority of

General Manager
Research and Development Department

Research Department, Engineering Division
BRITISH BROADCASTING CORPORATION

(T-24)

1993

© British Broadcasting Corporation

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without prior permission.

PREDICTED COVERAGE OF A COFDM SINGLE FREQUENCY NETWORK FOR UHF DIGITAL TERRESTRIAL TV BROADCASTING

M.B.R. Lee, Ph.D., D.I.C., A.M.I.E.E.

1. Introduction 1

2. Single Frequency Networks 1

3. Network Coverage Prediction 2
   - 3.1 Field strength calculation 2
   - 3.2 Minimum field strength and carrier-to-noise ratio 2
   - 3.3 Ensemble data rate and carrier spacing 2
   - 3.4 Prediction scenarios 2
   - 3.5 Additional predictions 4

4. Analysis of Coverage 4
   - 4.1 Coverage analysis program 4
   - 4.2 Analysis parameters 5

5. $C/(N+I)$ Distribution Results 5

6. Location Variation Model Results 5

7. Conclusions 7

8. References 8

Appendix: Prediction Method 9

© BBC 2005. All rights reserved. Except as provided below, no part of this document may be reproduced in any material form (including photocopying or storing it in any medium by electronic means) without the prior written permission of BBC Research & Development except in accordance with the provisions of the (UK) Copyright, Designs and Patents Act 1988.

The BBC grants permission to individuals and organisations to make copies of the entire document (including this copyright notice) for their own internal use. No copies of this document may be published, distributed or made available to third parties whether by paper, electronic or other means without the BBC's prior written permission. Where necessary, third parties should be directed to the relevant page on BBC's website at http://www.bbc.co.uk/rd/pubs/ for a copy of this document.

PREDICTED COVERAGE OF A COFDM SINGLE FREQUENCY NETWORK FOR UHF DIGITAL TERRESTRIAL TV BROADCASTING

M.B.R. Lee, Ph.D., D.I.C., A.M.I.E.E.

1. INTRODUCTION

The use of digital techniques for transmission systems can confer considerable advantages including the ability to reduce the information rate greatly using data compression techniques. This BBC Research Department Report looks at the application of digital techniques to terrestrial television broadcasting to the home, using a network of transmitters all operating synchronously in the same UHF channel. This has come to be referred to as a single frequency network or SFN[1].

Experience with digital audio broadcasting (DAB)[2, 3] suggested the possibility of using a single frequency network for digital video broadcasting (DVB). This would, of course, require a free channel. In the UK there are four channels in the UHF spectrum (Band IV channels 35 to 38) that are either unused (channels 35 and 37)* or have non-broadcast uses (airport radar in channel 36 and astronomy in channel 38).

Analogue terrestrial television transmission is well known to suffer from the effects of multipath propagation; this causes ghost images and/or causes spectral distortion as evidenced by reception errors in the ratio between the vision, sound and colour sub-carriers. In a digital environment the ghost images are manifested as inter-symbol interference and the spectral distortion remains a problem. These effects will be greatly enhanced by any attempt to use a non-directional receiving antenna and by the existence of multiple transmission sources.

A popular modulation technique for high data rate terrestrial transmission systems is Coded Orthogonal Frequency Division Multiplex or COFDM[4]. This provides a very high degree of tolerance towards multipath interference. Three factors contribute towards this tolerance; the inclusion of a guard interval, coding to provide error correction and the division of the digital data amongst a very large number of low bit rate carriers. It follows from this that a national network of co-channel transmitters can be developed such that not only do neighbouring transmitters not cause mutual interference but can combine in a constructive manner. This is the principle of the Single Frequence Network, or SFN.

The lower minimum required carrier-to-noise ratio (*C/N*) of a digital system when compared to a conventional analogue system means that a lower ERP is required in a given environment for the same quality of service. This was confirmed by tests carried out at BBC Research Department in 1992 using the Thomson/LER 'Diamond' system. Further tests are currently (September 1993) being undertaken using a larger ERP and a later version of the Thomson modem. A Research Department Report covering these tests will be produced subsequently.

The impact of a co-channel broadband digital signal on PAL is similar to that of white noise; as such, it is less severe than a PAL signal would be when considering the potential interference to the (unstabilised) UHF PAL outputs of video recorders operating within the channel range 35 to 38. This together with the lower ERP requirement, suggests that a digital SFN operating on channel 35 or 37 would not create the same order of VCR retuning problem which constrained the recent proposals for a fifth television channel.

2. SINGLE FREQUENCY NETWORKS

The use of the COFDM system for digital terrestrial television broadcasting (DVB) may allow the use of a single frequency network, as is the case with DAB. A guard interval of 250 μs has been selected as suitable for a national terrestrial SFN for DAB. DAB uses QPSK modulation; the higher bit rate likely for DVB will require a higher-order modulation scheme, such as 64-QAM. This will require carrier-to-interference and carrier-to-noise ratios about 12 dB higher than those for QPSK. The *C/N* requirement can be dealt with by increased power and/or increased receive antenna gain, whereas the *C/I* requirement may necessitate a longer guard interval than that for DAB in order that more distant transmitters do not interfere. In a homogeneous network of transmitters, one could postulate that the field strength from all transmitters at distance d will decay as $1/d$ rather than $1/d^2$ and so the requirement for 12 dB less interference suggests that the guard interval might need to be four times as great as that for DAB (i.e. up to 1 millisecond).

Weighed against this, though, is the probability that, particularly at UHF, terrain screening will restrict the signal level from more distant interferers.

---

* At the time of writing, a proposed new analogue service using these channels has not materialised.

Additionally TV reception could be planned on the basis of the use of a directional *and* roof mounted antenna.

As the guard interval is lengthened, the active symbol period must be lengthened proportionally if the ensemble data rate is to be maintained. This will result in a greater number of more closely-spaced carriers, so it is necessary to consider the question of local oscillator phase noise and any measures that can be taken to reduce its effect in practical receivers. It is known that this subject is under study and that potential solutions may exist. In this Report it is assumed that such solutions can be found, so as to demonstrate the benefits in spectrum utilisation that might be achieved.

In order to evaluate the inter-relationships between *C/I*, antenna directivity and guard interval length, an *ad hoc* transmission network was formulated for the purpose of performing computer simulations. This network consisted of 128 UHF transmitters sited, in general, at the locations of existing UK high and medium power transmitters. The computer simulations were based upon the software previously developed for DAB planning[5], with the addition of the possibility of specifying a directional receiving antenna.

3. NETWORK COVERAGE PREDICTION

3.1 Field strength calculation

The field strength predictions were performed using a receiver antenna height of 10 metres above ground level and a frequency of 585 MHz (channel 35). 50% time field strengths were used for contributing signals and 1% time field strengths for interfering signals, to ensure protection for 99% time. Field strengths were calculated using the BBC method for prediction of path loss over a terrain profile[6]. The transmitter locations were as shown in Fig. 1.

It should be noted that no sources of interference have been considered in this study other than thermal noise and co-channel interference from other transmitters in the SFN. Account cannot be taken of image and oscillator interference because there is no general agreement as to what the IF parameters for a digital receiver are to be. Even if these were defined, the effects of image transmissions would be dependent on the channel allocations made available for any new digital service.

3.2 Minimum field strength and carrier-to-noise ratio

The minimum field strength (strictly, for a multicarrier system, minimum power flux density) is determined by the required *C/N*. Current DAB studies suggest that, in a typical multipath (Rayleigh) channel and with error protection, an average *C/N* of 14 dB measured in the signal bandwidth must be achieved. However, DVB will require a higher order modulation scheme, such as 64-QAM, than the QPSK used for DAB. The value of E_b/N_0 required by 64-QAM is about 12 dB above that for QPSK; assuming similar channel and coding conditions this means that DVB will require an average *C/N* 12 dB higher than DAB. A further 1 dB 'implementation margin' (to cater for the increased complexity of a multi-level modulation system) is then added to give a required *C/N* for DVB of 27 dB.

The minimum field strength required to yield the minimum required *C/N* relative to thermal noise has been calculated at 48 dB(μV/m), assuming the use of a directional receiving antenna with a forward gain of 12 dB relative to a dipole. If a vertical dipole were used, to give omnidirectional reception, the minimum required field strength would therefore be 12 dB higher, namely 60 dB(μV/m).

3.3 Ensemble data rate and carrier spacing

The COFDM ensemble data rate *R* (Mbits/s) is given by:

$$R = \frac{N.B}{(1+\Delta/t_S)}$$

where N = number of bits/carrier

B = ensemble bandwidth (MHz)

Δ = guard interval

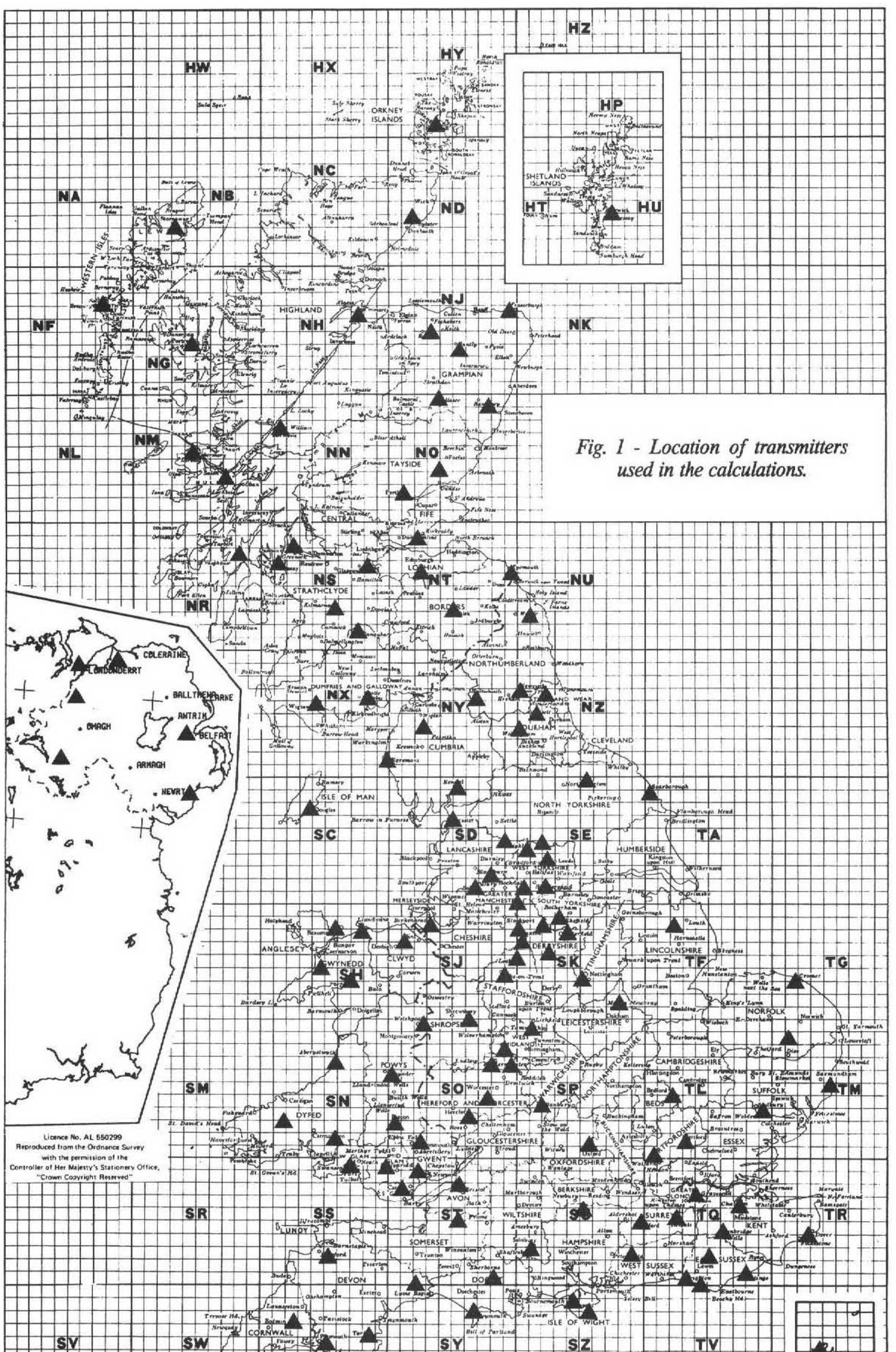
t_S = active symbol period

Thus the ensemble data rate remains constant as long as Δ/t_S is constant, irrespective of Δ or t_S. The carrier spacing is $1/t_S$.

Lengthening of Δ gives greater protection against delayed signals, but at the expense of a larger number of more closely spaced carriers if the ensemble data rate is to be maintained. For example, if $t_S = 4\Delta$ then a guard interval of 250 μs will require an active symbol period of 1 ms. This implies a carrier separation of 1 kHz and hence about 8000 carriers in an ensemble of 8 MHz bandwidth.

3.4 Prediction scenarios

A range of scenarios has been examined for coverage from the SFN. Four values of the guard interval Δ were used: *250 μs*, *500 μs*, *750 μs* and 1000 μs. The active symbol period t_S was assumed to be always four times the guard interval. This is the



Licence No. AL 550299
Reproduced from the Ordnance Survey
with the permission of the
Controller of Her Majesty's Stationery Office,
"Crown Copyright Reserved"

Fig. 1 - Location of transmitters used in the calculations.

same as Mode 1 DAB, and represents an effective power loss of 1 dB. For each value of guard interval two variations were examined: domestic directional or omnidirectional receiving antenna. A stylised radiation pattern was assumed for the domestic directional antenna, with a front to back ratio of 15 dB and correction falling linearly from 0 dB at ±20° to −15 dB at ±60° relative bearing. Note that this pattern is within 1 dB of that specified in CCIR Recommendation 417.

Coverage has been generated for both variations, for all four values of Δ. The other prediction parameters were as shown below. The values for receiver dynamic range and late lock threshold influence the behaviour of the algorithm that selects the reference transmitter.

Calculation increment	1 km
Cut-off distance	500 km
Receiver dynamic range	13 dB
Late lock threshold	10 dB
Minimum C/N	27 dB
Minimum C/I	24 dB

All transmitters were assumed to be transmitting synchronously (i.e. they would all transmit a given symbol simultaneously). The prediction method is described in the Appendix.

Plots of the results for the coverage predictions for both variations at $\Delta = 250\ \mu s$ and $\Delta = 500\ \mu s$ are presented in Figs. 2 to 5 *(between pages 4 and 5)*. The colours represent 50% location values of C and $C/(N+I)$ as shown below:

Coverage plot colours

Green	C above minimum, $C/(N+I)$ 0 to 12 dB above minimum
Yellow	C above minimum, $C/(N+I) >$12 dB above minimum

where:

minimum $C = 48$ dB(μV/m) or
60 dB(μV/m) as appropriate

minimum $C/(N+I) = 27$ dB

The unshaded areas indicate where C and/or $C/(N+I)$ is below minimum, or where no calculations were performed. Note that the case of inadequate C but adequate $C/(N+I)$ cannot arise; this is because the minimum wanted field strength specified for generating the coverage plots is that required to produce the minimum C/N to overcome thermal noise.

3.5 Additional predictions

Considerations of local oscillator phase noise and receiver processing power may limit the carrier separation for a COFDM ensemble for DVB. In order to assess the effect this may have on the coverage, the calculations were repeated for a carrier separation of 4 kHz, corresponding to a maximum active symbol period t_S of 250 μs. If the data rate is to be maintained, this requires a reduction of the guard interval Δ to 62.5 μs.

4. ANALYSIS OF COVERAGE

The coverage prediction program generates 50% location values for the contributing and the interfering fields for a given 1 km square, and from these derives a 50% location value for $C/(N+I)$. The resultant 50% location $C/(N+I)$ distribution can then be analysed using a range of simple models for the behaviour of the contributing field C and interfering field I. The prediction program also identifies a contributing or interfering transmitter as being a dominant source if it delivers more than half the received contributing or interfering power.

The proportion of any given 1 km square that is served will depend on the location variations of the fields within the square. Until the location variations can be predicted, it is only possible to explore the results of applying some simple models to the predicted 50% location values.

4.1 Coverage analysis program

The coverage analysis program takes a user-specified minimum required $C/(N+I)$, a user-specified minimum C, a user-specified standard deviation σ and the predicted 50% location $C/(N+I)$ for a given 1 km square, and from these derives the proportion of the area of the square that is served. This also gives the proportion of the population of the square that is served, on the assumption that the population is evenly distributed within the square. The program also generates and analyses the distributions of population and area vs. 50% location C and $C/(N+I)$.

The analysis results presented in this Report were generated using an analysis model which makes use of the dominant source information. If there is a dominant source then the field in question (C or I) is assumed to exhibit a log-normal location variation with standard deviation σ, otherwise it is assumed to be uniform within a 1 km square. C and I are assumed to be uncorrelated. Thus the standard deviation of $C/(N+I)$ for a given 1 km square will be zero, σ, or $\sigma^*\sqrt{2}$. The population and area

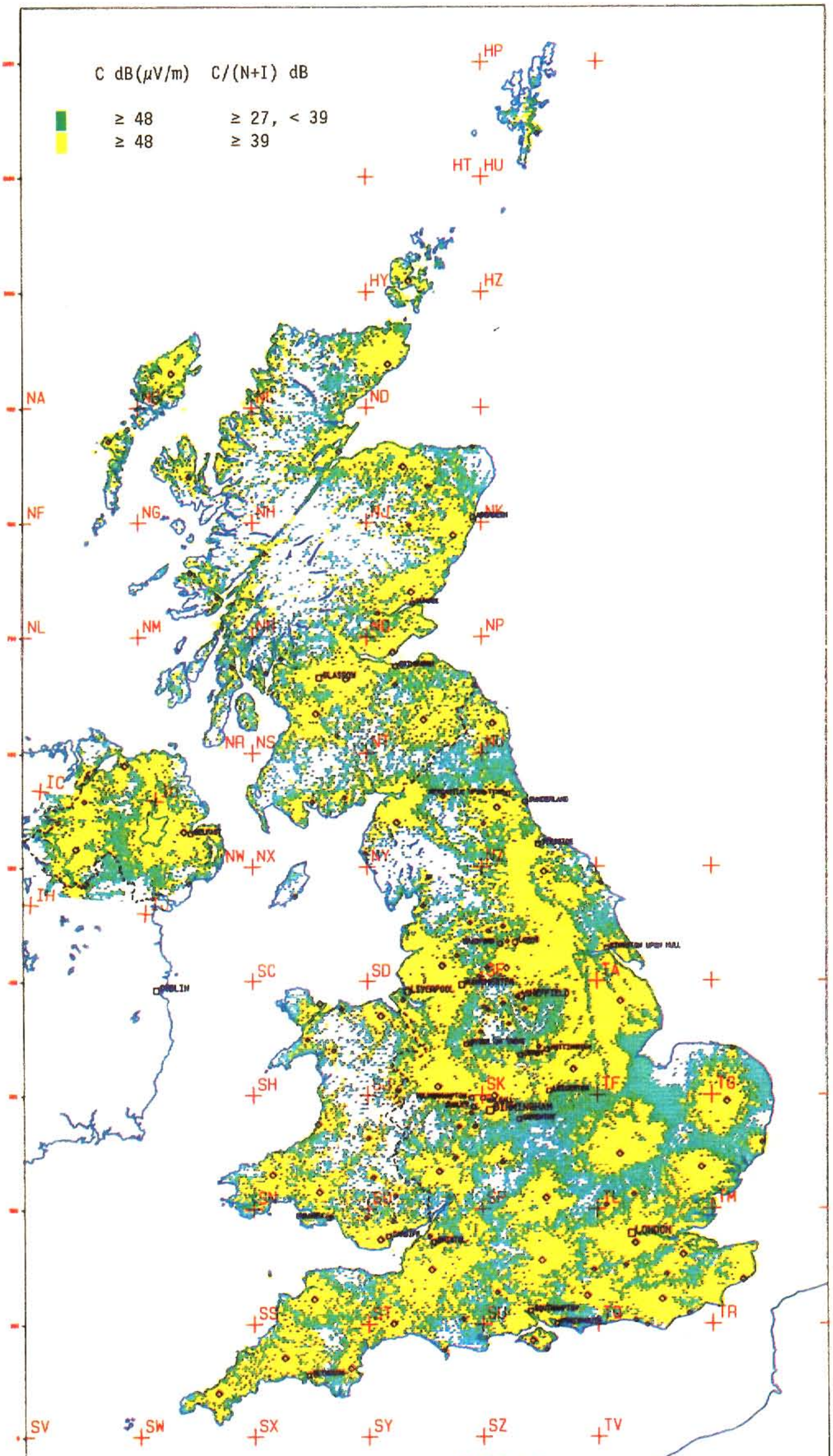


Fig. 2 - Predicted SFN coverage for Δ = 250 μs, directional antenna.

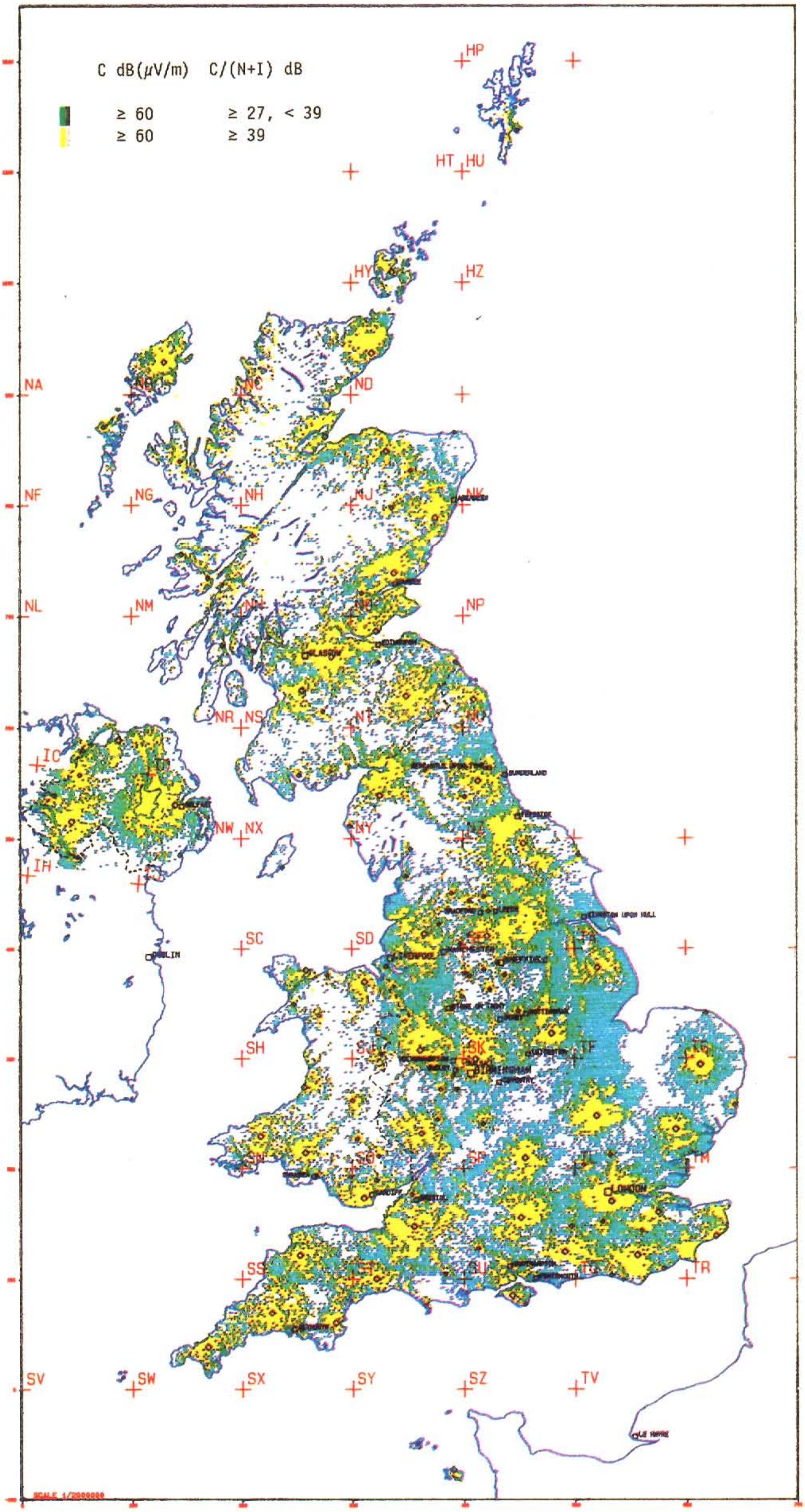


Fig. 3 - Predicted SFN coverage for Δ = 250 μs, omnidirectional antenna.

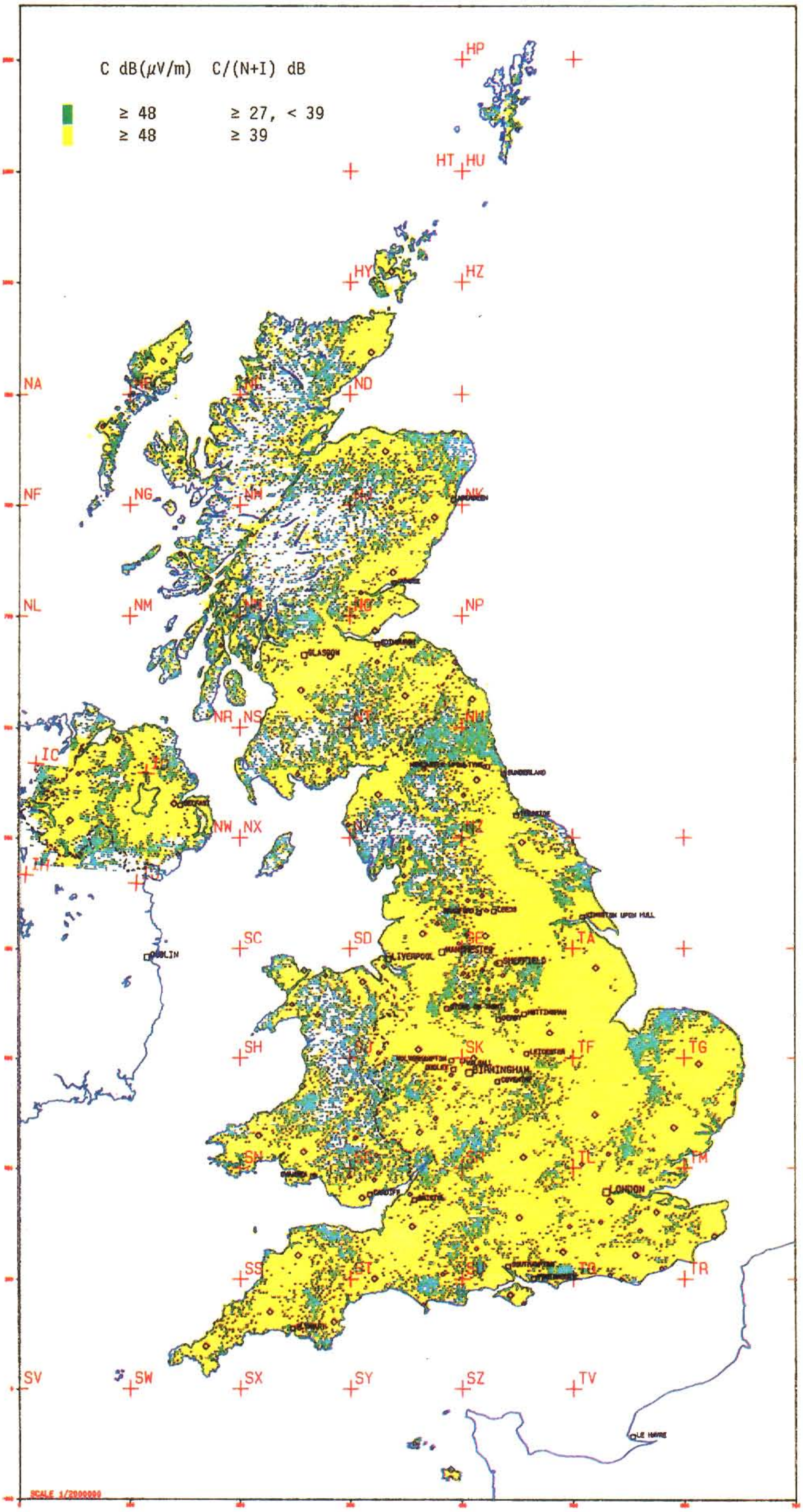


Fig. 4 - Predicted SFN coverage for Δ = 500 μs, directional antenna.

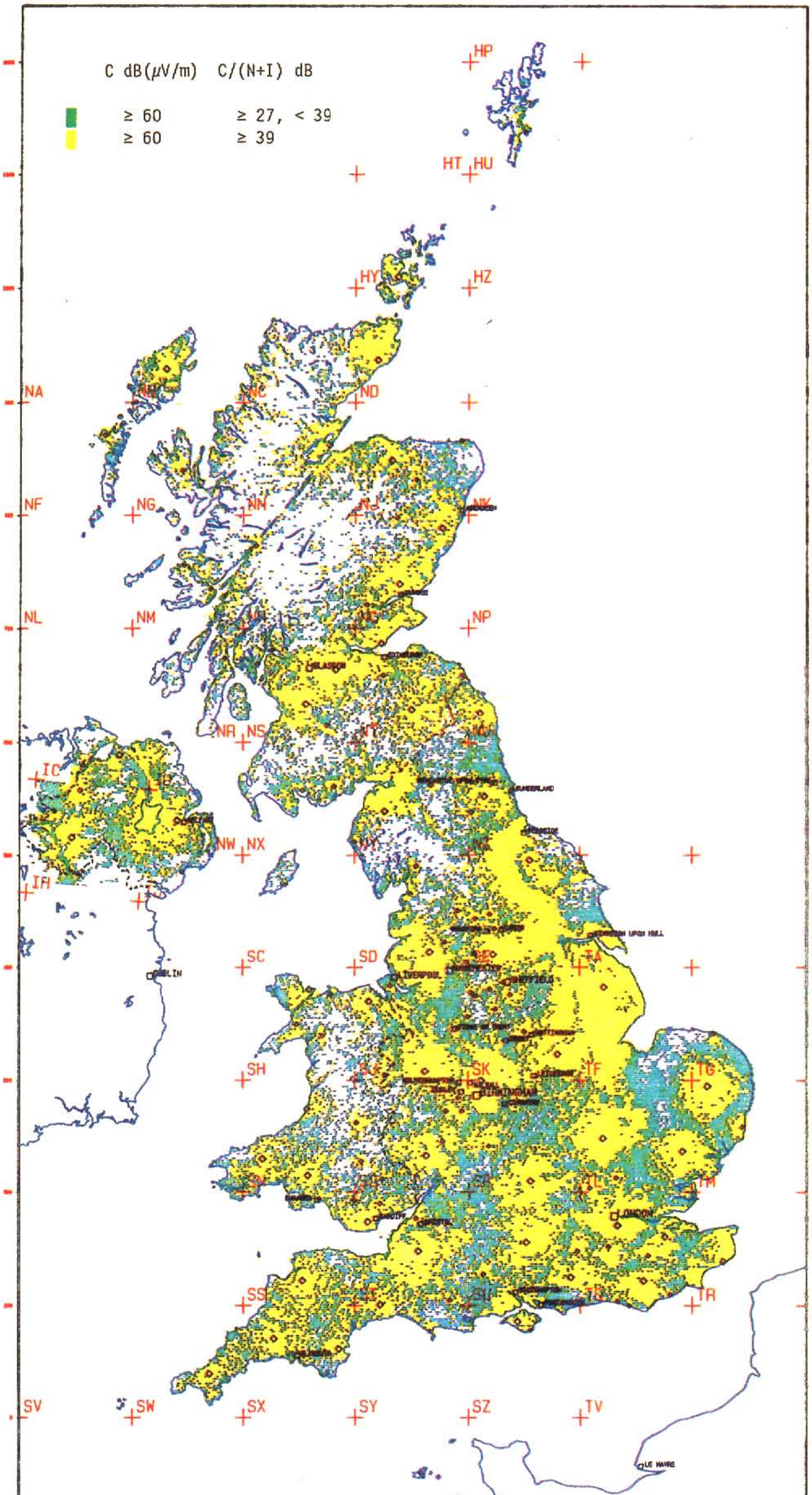


Fig. 5 - Predicted SFN coverage for Δ = 500 µs, omnidirectional antenna.

percentages are generated by simply accumulating the served proportions of all the 1 km squares*.

4.2 Analysis parameters

The analysis parameters were as shown below:

Minimum $C/(N+I)$	27 dB
Minimum C	48 dB(μV/m) or 60 dB(μV/m) as appropriate
Single signal standard deviation	5.5 dB

The same value of standard deviation was used as that found for DAB in Band III. This value may or may not be correct for a COFDM ensemble of greater bandwidth and at a higher frequency delivered to a rooftop antenna. A standard deviation of 5.5 dB is equivalent to a 50% to 99% location correction factor of 12.8 dB.

The results of the analysis of the coverage are presented in Tables 1 and 2. The tables include the results for the additional predictions ($\Delta = 62.5\ \mu s$).

5. C/(N+I) DISTRIBUTION RESULTS

Some interesting results are immediately apparent from the analysis. Consider first the distributions of population and area vs. 50% location $C/(N+I)$ exceeded for the various values of Δ, as shown in Figs. 6 and 7 *(overleaf)*, and also in Table 1. Changing from a directional to an omnidirectional antenna consistently reduces the mean $C/(N+I)$ by about 10 dB. It is also apparent from these results that lengthening the guard interval from 250 μs to 500 μs produces a significant improvement in the mean $C/(N+I)$ of about 10 dB, but any further increase yields relatively little extra benefit.

It is clear from Table 1 that the mean of the population vs. $C/(N+I)$ distribution consistently exceeds that of the area vs. $C/(N+I)$ distribution by about 10 dB. This is reflected in Figs. 6 and 7. This result stems from the fact that transmitters tend to be concentrated near centres of population; the distributions of population and transmitters are therefore not independent. $C/(N+I)$ is high near transmitters, so the population is concentrated in areas of higher $C/(N+I)$ whereas the area is (obviously!) uniformly distributed.

Table 1: Mean value of 50% location C/(N+I) dB for whole UK by population and by area.

Δ (μs)	Antenna Directional	 Omnidirectional
	Population	
62.5	32.2	23.2
250	46.7	37.7
500	56.5	46.1
750	59.2	48.3
1000	59.8	48.8
	Area	
62.5	24.9	17.3
250	36.0	28.1
500	44.5	35.3
750	47.8	37.7
1000	49.0	38.6

Table 2: Percentage population and area coverage for whole UK.

Δ (μs)	Antenna Directional	 Omnidirectional
	Population	
62.5	63	38
250	90	78
500	97	91
750	98	93
1000	98	93
	Area	
62.5	43	24
250	69	53
500	82	69
750	85	73
1000	87	75

The analysis of the additional prediction distributions confirms the trend seen in the main set of results. The change in mean $C/(N+I)$ caused by reducing Δ from 250 μs to 62.5 μs is even greater than that arising from increasing Δ from 250 μs to 500 μs.

6. LOCATION VARIATION MODEL RESULTS

Table 2, and Figs. 8 and 9 *(overleaf)*, show the percentage population and area coverage for the whole UK for the various values of Δ. Some words of

---

* An alternative method of generating the population and area percentages is to require that a certain minimum proportion of a given 1 km square must be served. All the population and area of those squares which reach this proportion are added to the population and area accumulators. This Yes/No model is considered to be excessively stringent for a DVB service to fixed installations; it is more appropriate for a DAB service to mobile installations where the user is not free to decide the antenna position.

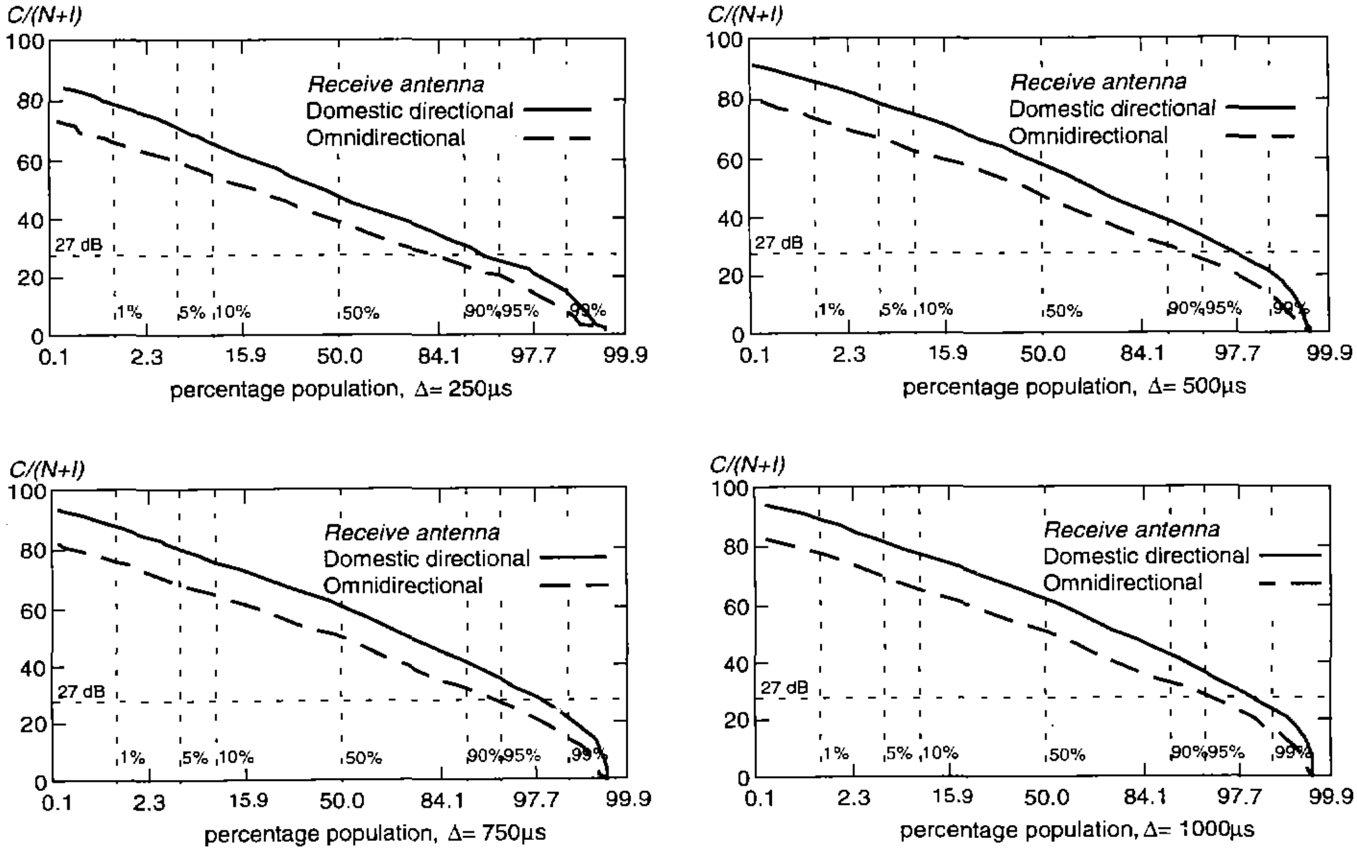


Fig. 6 - Cumulative distributions of percentage ***population*** *vs. 50% location C/(N+I) exceeded (dB) for four values of Δ.*

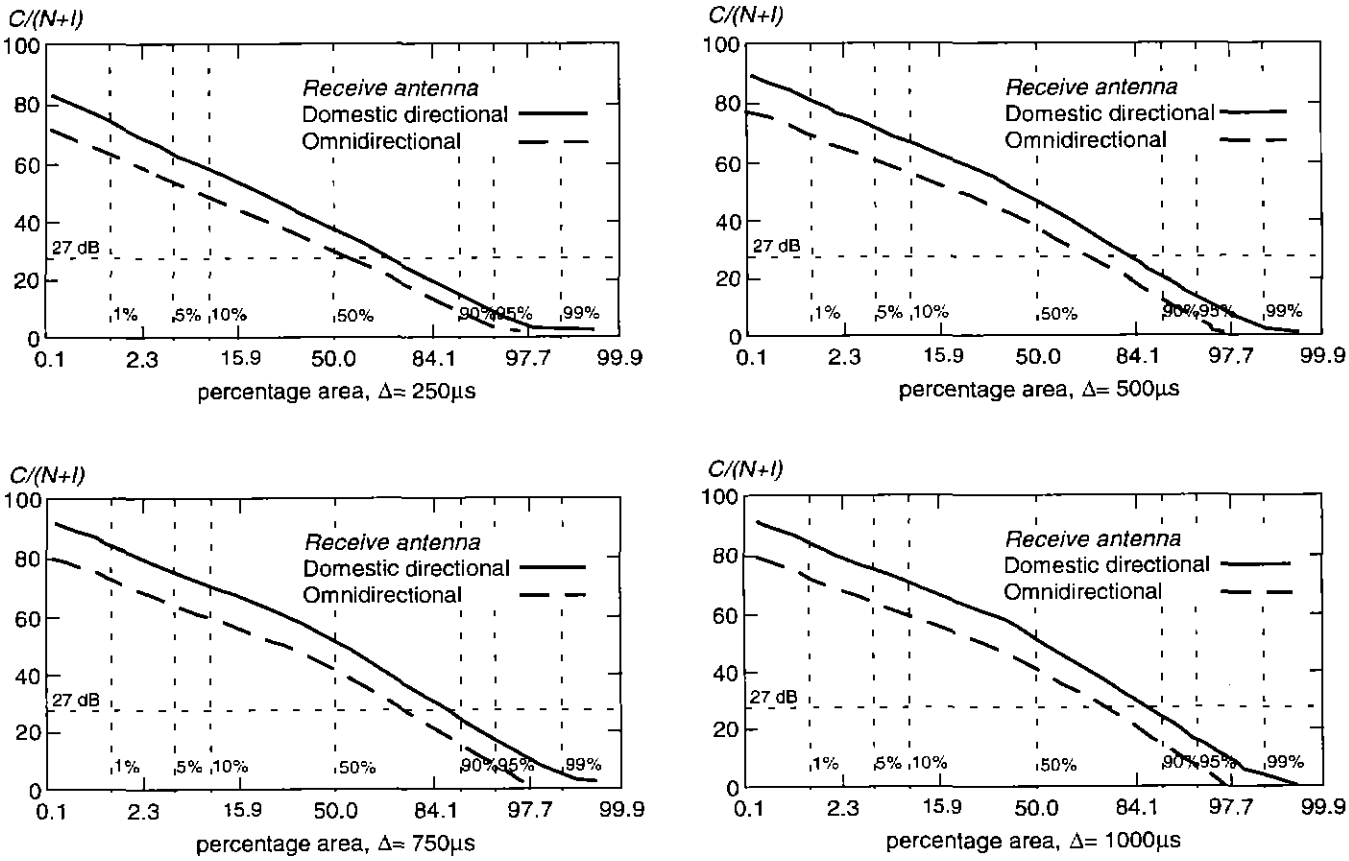


Fig. 7 - Cumulative distributions of percentage ***area*** *vs. 50% location C/(N+I) exceeded (dB) for four values of Δ.*

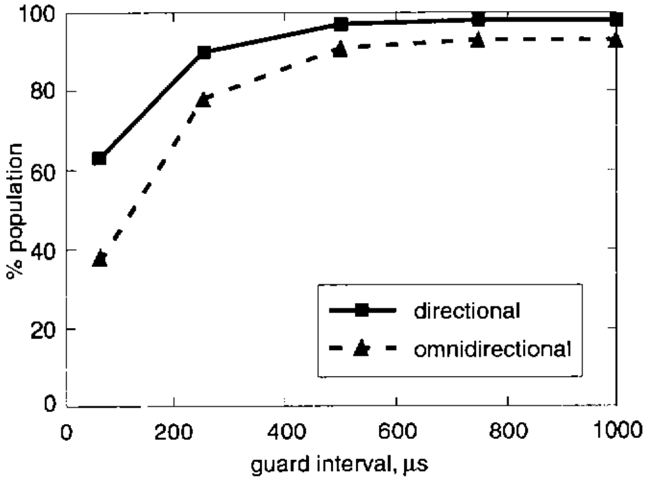


Fig. 8 - The percentage ***population*** *coverage for the whole of the UK for various values of guard interval.*

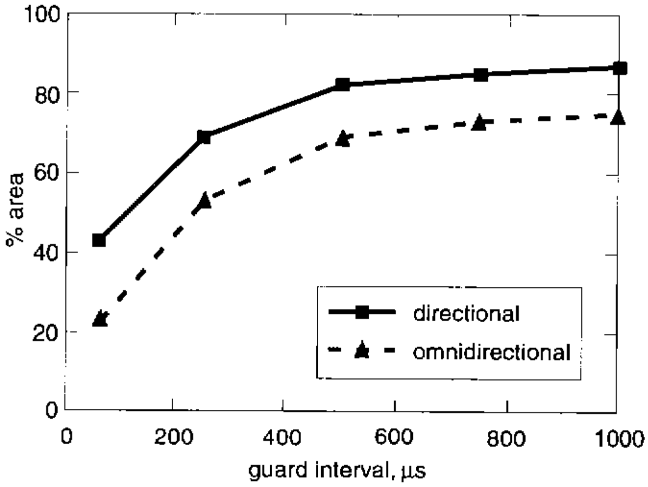


Fig. 9 - The percentage ***area*** *coverage for the whole of the UK for various values of guard interval.*

caution should be noted regarding these results. The nature of the location variation of $C/(N+I)$ is still an open question; the coverage analysis results presented here are only the application of a simple statistical model to the predicted 50% location values. For instance, the 99% location value of $C/(N+I)$ cannot be predicted until the location variation of a single signal is known, and until the degree of correlation between multiple signals at any given point can be predicted.

It is the location variation of $C/(N+I)$ within a small area rather than the variation of C which will limit the coverage. The latter may, subject to co-ordination with adjacent countries, be handled by raising the ERP and hence raising the 50% location value of C, but this will have no significant effect on the 50% location value of $C/(N+I)$. (*Note that interference from transmission sources outside the network have not been considered here.*)

The results for the additional prediction coverage analysis show that reducing the guard interval to 62.5 µs dramatically reduces the network coverage. It is clear that a relatively sparse transmitter network such as that considered in this Report will not provide continuous coverage if the guard interval is short.

7. CONCLUSIONS

An initial planning exercise has been carried out for a possible single frequency network for digital terrestrial television broadcasting. A range of values of guard interval Δ were used, from 62.5 µs to 1000 µs. For each value of guard interval two variations were examined, namely domestic directional or omnidirectional receiving antenna.

Use of an omnidirectional receiving antenna is found to reduce the mean 50% location value of $C/(N+I)$ by about 10 dB, for all values of Δ. Lengthening the guard interval Δ from 62.5 µs to 250 µs and then to 500 µs produces significant improvements in $C/(N+I)$, but relatively little benefit is gained by lengthening Δ further.

Either of these results can be compared with the 12 dB extra $C/(N+I)$ required for 64-QAM relative to QPSK modulation. If the COFDM multiplex is carrying an HDTV signal encoded in such a way that a standard definition picture can be recovered by decoding the 64-QAM as QPSK, then it could be argued that this will provide an adequate service for the cases where 1% time interference *or* the use of an omnidirectional antenna causes $C/(N+I)$ to fall below the minimum value of 27 dB.

Overall, the results show that the use of a directional antenna improves the carrier-to-interference ratio by a factor almost equal to the antenna gain. This provides most of the additional performance needed for a 64-QAM system compared with QPSK. With such antennas mounted at roof level it should be possible to serve in excess of 90% of the population from the 128 transmitters as specified for the model; fine tuning the network by moving transmitters, adjusting their powers or adding additional ones, *can only improve* the results! It is important to note that interference to and from transmissions outside the network has not been considered in the calculation and assessment of coverage. In practice, this would restrict the coverage that could otherwise have been achieved.

In the presence of tropospheric interference, the $C/(N+I)$ in some areas will fall below the 27 dB needed for successful 64-QAM decoding. Increasing the guard interval beyond 250 μs would reduce the size of such areas but not eliminate them. On the other hand, many tropospheric interference problem areas could be eliminated by using fill-in transmitters. Alternatively, a hierarchical modulation system could provide standard definition during times of adverse interference.

A denser network of transmitters will tend to produce better figures for $C/(N+I)$ and hence may give adequate coverage with a shorter guard interval. However, even the shorter guard interval implies an active symbol period of at least 1 ms and hence about 8000 carriers in an ensemble of 8 MHz bandwidth.

8. REFERENCES

1. POMMIER, D. and RATLIFF, P.A., 1988. New prospects for high-quality digital sound broadcasting to mobile, portable and fixed radio receivers. International Broadcasting Convention, September 1988. IEE Conference Publication No. 293, pp. 349-353.

2. SHELSWELL, P., *et al*, 1991. Digital Audio Broadcasting: the first UK field trial. BBC Research Department Report No. BBC RD 1991/2.

3. BELL, C.P. and WILLIAMS, W.F., 1993. Coverage aspects of a single frequency network designed for digital audio broadcasting. BBC Research Department Report No. BBC RD 1993/3.

4. ALARD, M. and LASALLE, R., 1987. Principles of modulation and channel coding for digital broadcasting for mobile receivers. *EBU Review-Technical*, No. 224, August 1987, pp. 168-190.

5. LEE, M.B.R., 1993. Planning methods for a national single frequency network for DAB. 8th Int. Conf. on Antennas and Propagation, April 1993. IEE Conference Publication No. 370, pp. 940-947.

6. CAUSEBROOK, J.H., *et al*, 1982. Computer prediction of field strength: a manual on methods developed by the BBC for the LF, MF, VHF and UHF bands. BBC Research Department.

7. NEWLAND, J.D., 1988. Investigation of mutual interference between digitally modulated signals. BBC Research Department Report No. BBC RD 1988/13.

APPENDIX

Prediction Method

In an SFN, the receiver will generally receive more than one signal; firstly, due to multipath propagation (short relative delays) and secondly, from multiple transmitters (longer relative delays). No attempt is made in the present work to assess the impact of multipath propagation on the coverage area; we are concerned with the impact of delayed signals from the multiple co-channel transmitters of an SFN.

Signal combination

Signals arriving at the receiver will contribute to or detract from the overall system performance to an extent determined by their delay (positive or negative) relative to the start of the receiver symbol period. The dependence on relative delay of the contributing proportion α_i of the received power from transmitter i is as follows:

$$\alpha_i = \begin{cases} 0, & \delta_i < -t_S \\ \left[1 - \left(\frac{-\delta_i}{t_S}\right)\right]^2, & -t_S \leq \delta_i < 0 \\ 1, & 0 \leq \delta_i \leq \Delta \\ \left[1 - \left(\frac{\delta_i - \Delta}{t_S}\right)\right]^2, & \Delta < \delta_i < t_S + \Delta \\ 0, & \delta_i \geq t_S + \Delta \end{cases} \qquad (1)$$

where δ_i = relative delay for transmitter i

Δ = guard interval

t_S = active symbol period

The prediction program

The prediction program calculates the combined contributing and interfering field strengths at regularly spaced test points within an area. Contributing and interfering proportions of the received powers from all the transmitters in the SFN are combined by power sum addition.

Before the field strength combinations at a given point can be carried out, it is necessary to determine the position in time of the start of the receiver symbol period; all the signal delays are relative to this point. Various receiver synchronisation strategies are possible, but for the present work it is assumed that the receiver will lock to the signal from a particular transmitter (which will thus have zero relative delay). This will not necessarily be the earliest arriving signal. Following discussions on the likely behaviour of the receiver in the presence of multiple signals of differing field strengths, a more elaborate strategy for determining the reference transmitter was developed, as described below.

Selection of reference transmitter

The reference transmitter is identified by the procedure 'FindRef', using individual field strengths already determined. Firstly, it calculates, by power sum addition, the total field strength at the receiver. It subtracts from this total field a user-specified receiver dynamic range, and then sets a threshold field strength as the greater of a user-specified noise level and the total field minus dynamic range.

The program then identifies both the earliest-arriving signal that exceeds this threshold and also the strongest signal. If these are one and the same, then that signal's transmitter is selected as the reference. If they are not the same, the first arriving signal identifies the reference transmitter unless the strongest signal exceeds the first-arriving signal by more than a user-specified 'late-lock threshold', in which case the strongest signal identifies the reference transmitter. If no signal exceeds the minimum field strength then no reference transmitter is identified and therefore no signal combination calculations are performed for the current test point.

Combination of signals

Having identified a reference transmitter, the program generates the combined contributing and interfering field strengths using the routine 'AddFields'. This routine divides the signal from each of the transmitters in the SFN between the contributing and interfering combined field strengths according to its delay, δ, relative to the reference transmitter.

The total contributing field in dB relative to 1 μV/m will be:

$$F_W = 10\log\left(\sum_i \alpha_i 10^{f_i/10}\right) \tag{2}$$

and the total interfering field will be

$$F_I = 10\log\left(\sum_i (1-\alpha_i) 10^{f_i/10}\right) \tag{3}$$

where f_i = field strength for transmitter i in dB(μV/m). The value of α_i is calculated from the relative delay, δ, using (1).

To assess the overall $C/(N{+}I)$ an equivalent noise field strength should be added to the interfering field. Co-channel interference to a QPSK signal from another QPSK signal is less damaging than the equivalent power of Gaussian noise[7]. The weighting factor to be applied to the interfering field will depend on the number of interfering sources, varying from about −4 dB for a single interferer to zero as the number of interferers tends to infinity. In practice there will be only one or a few significant interferers, so a value of −3 dB is considered appropriate. Thus the overall weighted interfering field is given by:

$$F_{I_w} = 10\log\left(10^{f_N/10} + 10^{(F_I-3)/10}\right) \tag{4}$$

where f_N = equivalent noise field strength in dB(μV/m). The overall weighted $C/(N{+}I)$ at the current test point is then $F_W - F_{I_w}$. As well as calculating the combined contributing and interfering field strengths, the AddFields routine also identifies the strongest contributing and interfering transmitters and returns their field strengths.

Printed by BBC RESEARCH DEPARTMENT, Kingswood Warren, Tadworth, Surrey, KT20 6NP